



HGTD Sensor Production of USTC-IME

Hang Yang

On Behalf of USTC ATLAS HGTD Sensor Group

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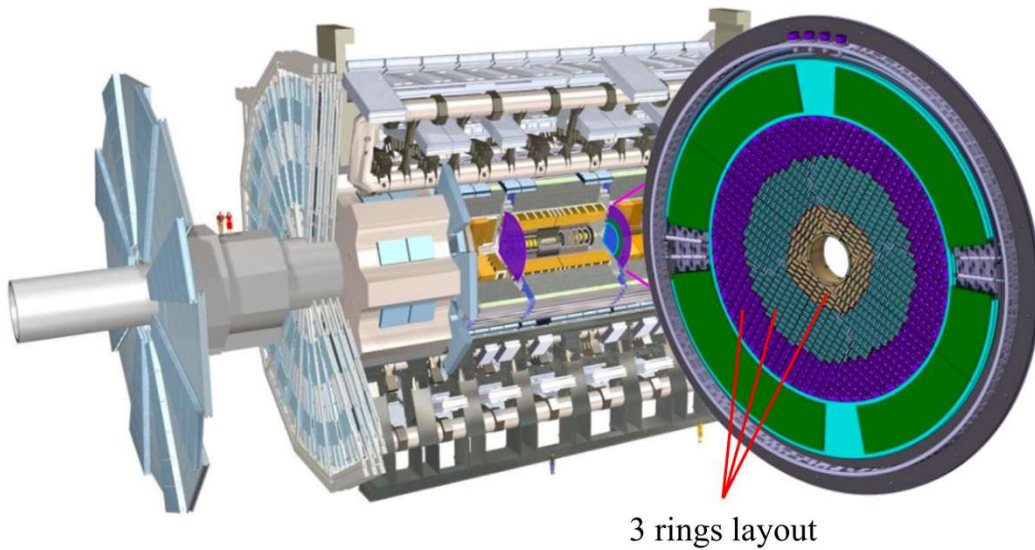
Outline

- HGTD requirements and USTC sensor development
- Performance characterization and radiation tolerance
- QC methods and validation
- Pilot and K1–K4 production results
- Summary

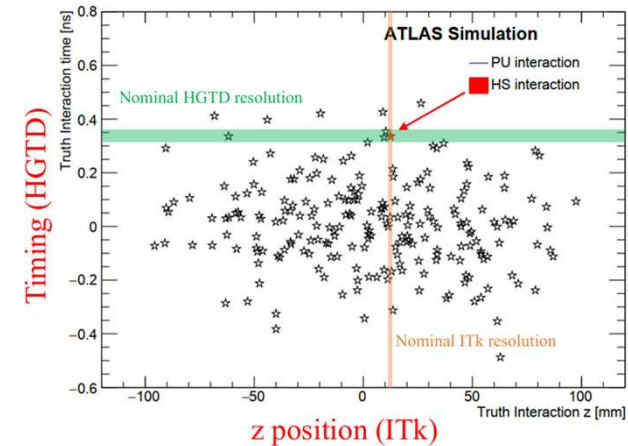
HGTD for the ATLAS HL-LHC upgrade

Precision timing for track–vertex association and pile-up rejection

Forward coverage: $2.4 < |\eta| < 4.0$, at $z \approx \pm 3.5$ m



HGTD between the tracker and endcap calorimeters

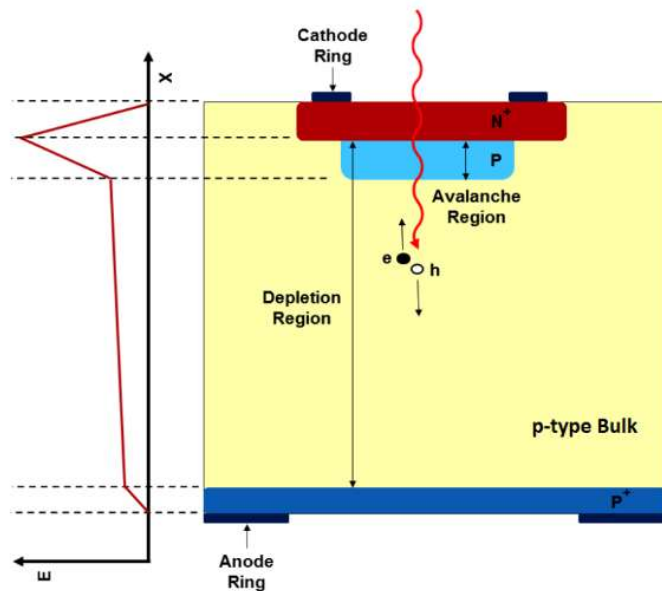


Quantity	Requirement
Track timing	< 50 ps
Radiation fluence	2.5×10^{15} neq/cm ²
Charge at end of life	> 4 fC
Sensor timing after irradiation	< 50 ps on test bench

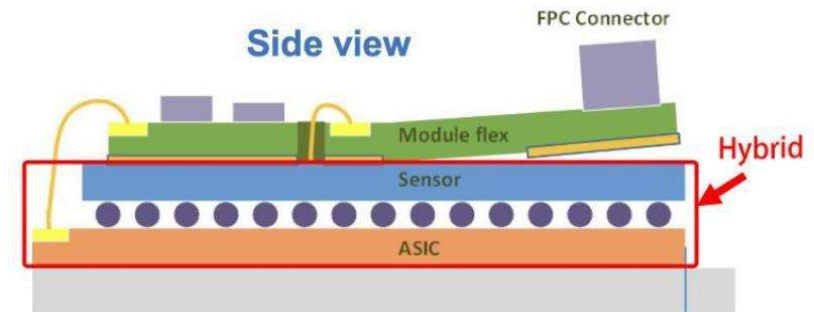
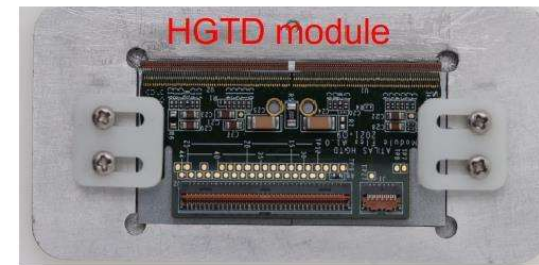
LGAD sensor and HGTD readout

A thin gain layer provides controlled avalanche multiplication

50 μm active silicon, 15×15 pads, $1.3 \times 1.3 \text{ mm}^2$ per pad



LGAD junction and gain region



Sensor-ALTIROC hybrid and module

USTC design and characterization, IME fabrication

USTC LGAD development

Design started in 2019, with successive process and layout improvements

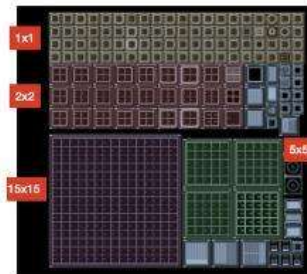
2020



USTC-1.0

First prototype
High leakage

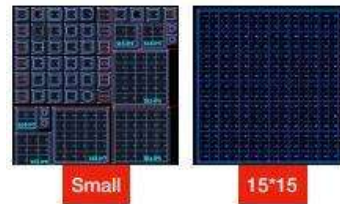
2020



USTC-1.1

Process refinement
GR leakage remained

2021



USTC-2.1

Improved uniformity
Improved VBD range

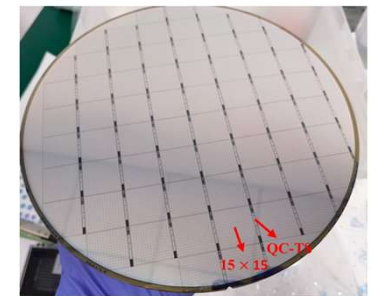
2022



Final Design Review
(FDR)

Final designs with
validated data
and plans

2024



USTC-IME pre-production
(v2.1 W17 as baseline)

USTC-pre

Based on 2.1-W17
15 × 15 + QC-TS
Pre-production / PRR

Current production: Pilot and K1–K4 batches, followed by wafer-level CQC

Performance requirements after irradiation

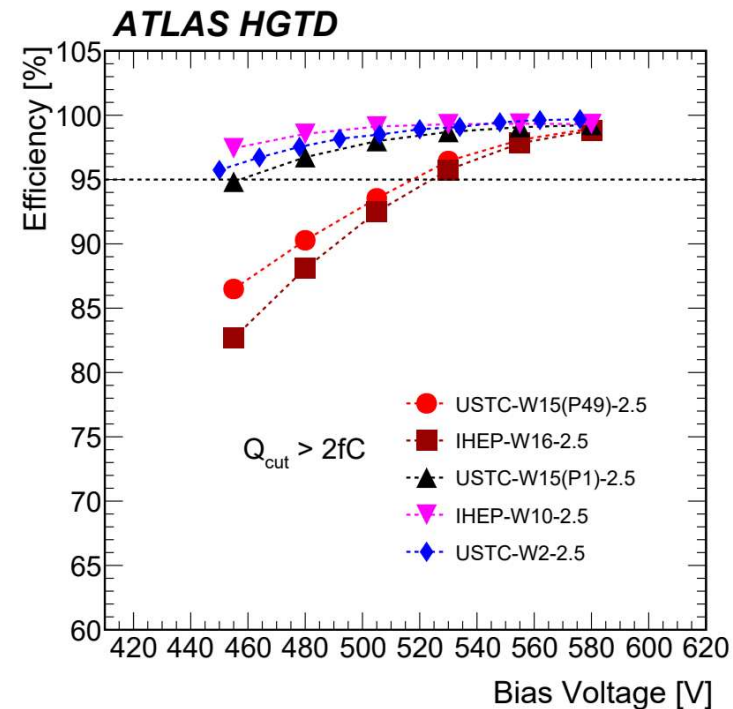
Timing performance requires sufficient charge and detection efficiency

Observable	Before	Irradiated
Charge MPV	>15 fC	>4 fC
Sensor timing	<40 ps	<50 ps
Central efficiency	>97%	>95%

End-of-life qualification

2.5×10^{15} neq/cm²

A common operating point must satisfy charge, timing and bias limits.

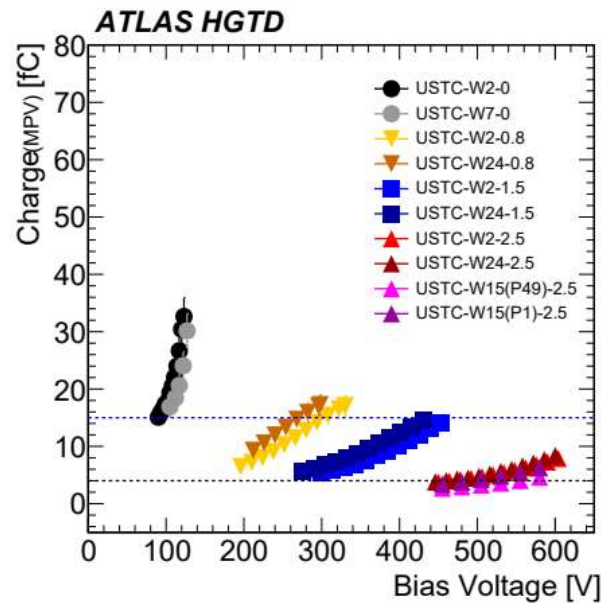


Beam efficiency: $-30\text{ }^{\circ}\text{C}$, $Q > 2\text{ fC}$

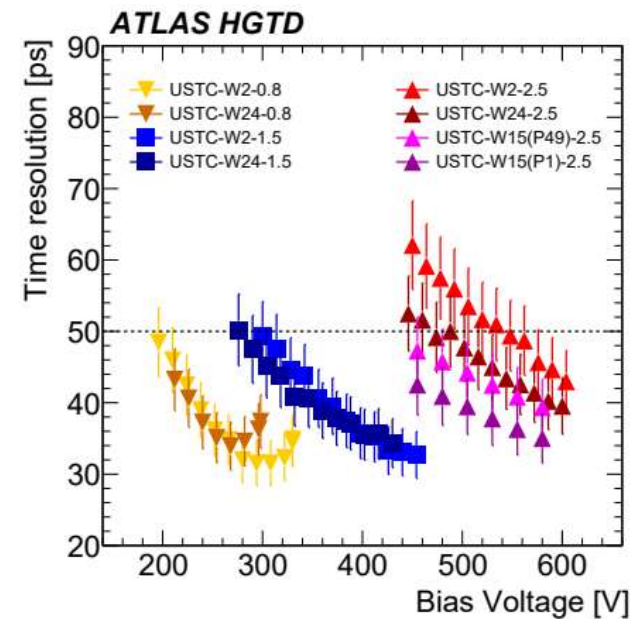
USTC pre-production performance

Beam-test evidence for the USTC pre-production design

Single-pad QC-TS samples, $-30\text{ }^{\circ}\text{C}$, fluences up to $2.5 \times 10^{15}\text{ neq/cm}^2$



Charge MPV versus bias



Sensor timing with 50% CFD

Conclusion: HGTD charge, timing and efficiency targets reached at suitable bias.

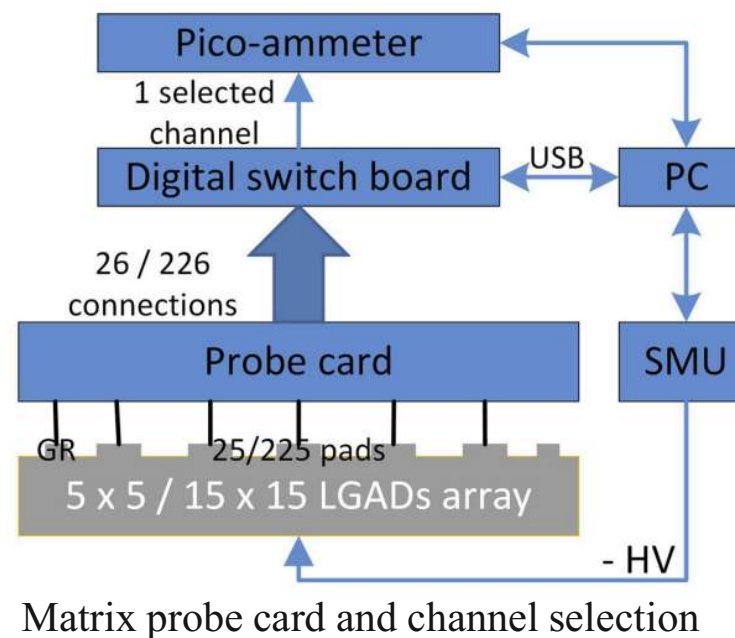
Pre-production validation provides the basis for production QC.

QC design: coverage and independent checks

CQC screens every sensor before assembly, SQC validates array operation

We used one batch: pre-production to verify the QC method and parameters

Stage	Measurement and decision
CQC All sensors	Per-pad I–V Breakdown, leakage, yield
SQC Selected sensors	Matrix I–V / C–V Uniformity and cross-check



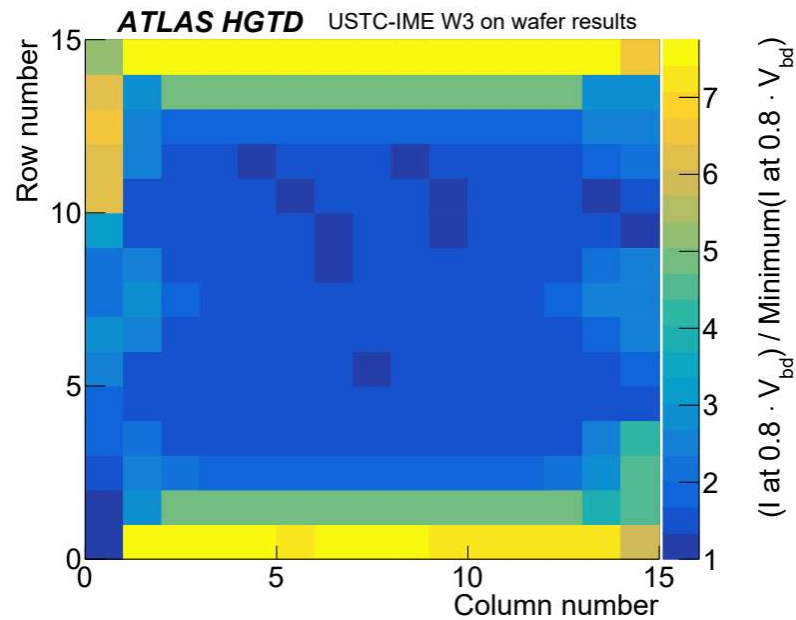
Radiation monitoring: irradiated QC-TS from each wafer

Electrical acceptance and radiation qualification provide complementary checks.

Pad boundary conditions affect leakage

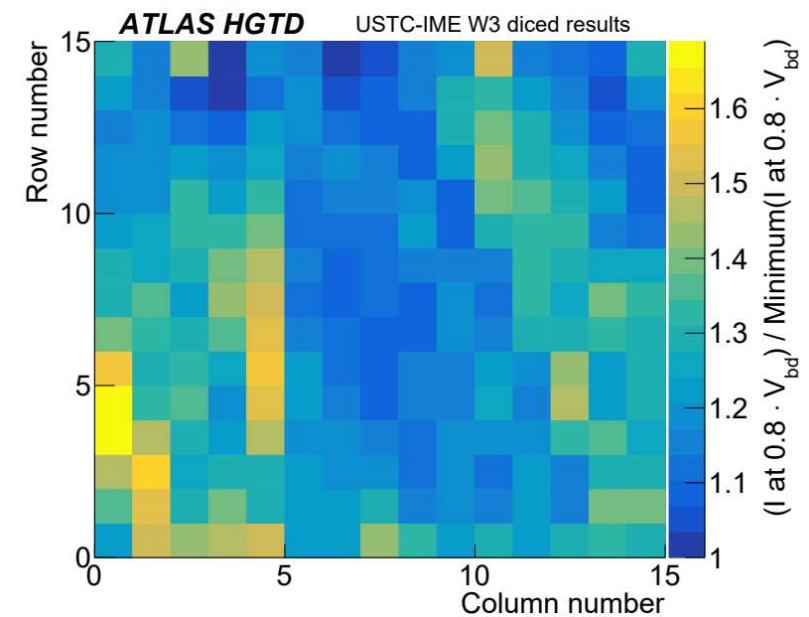
Matrix tests check uniformity with all pads held at a common potential

CQC needles: other pads floating



Outer rows show elevated normalized leakage

Probe card: other pads grounded



Full-array leakage ratio below 3

W3 pre-production example. Different color scales, temperatures and processing stages.

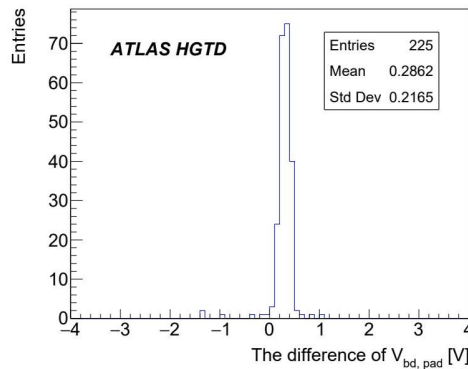
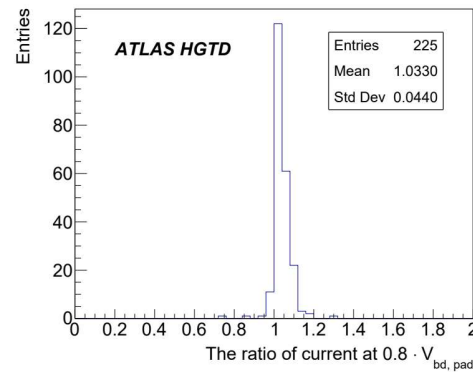
CQC validation under matched conditions

Processing and temperature checks explain the comparison with SQC

UBM and dicing

ΔV_{bd} within 2 V

Leakage ratio close to 1

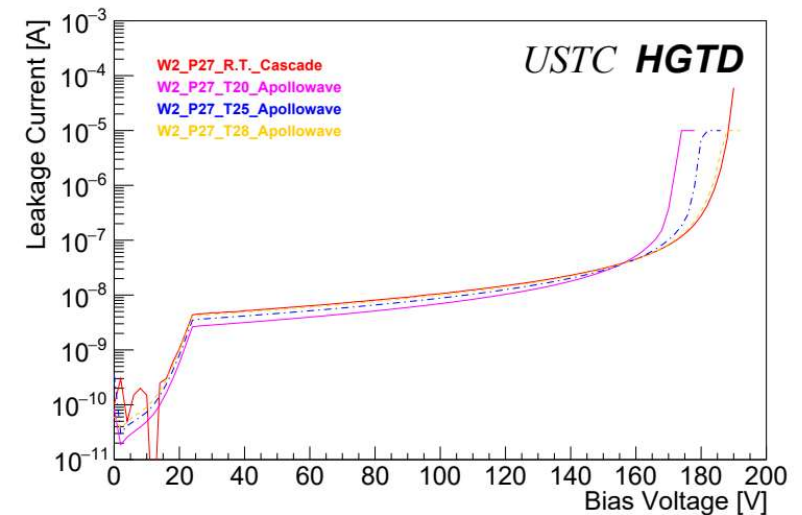


Matched probe configuration before / after processing

Controlled temperature

20 / 25 / 28 °C repeats

28 °C curves reproduce the earlier CQC

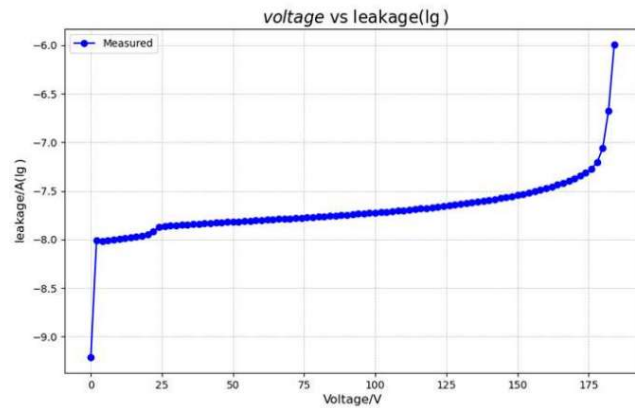


Repeated I–V scans on the same sensor

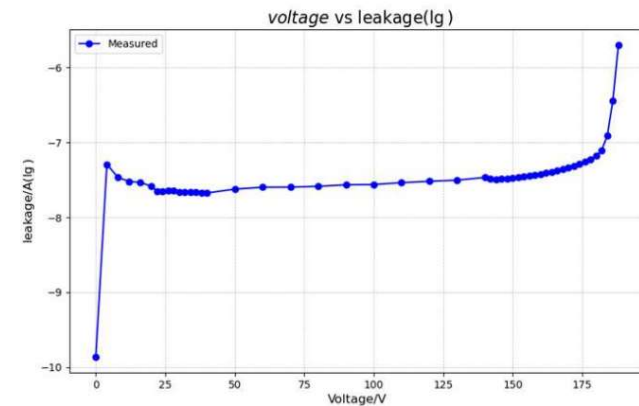
CQC setting : Segmented voltage scan and validation

Dense sampling near breakdown preserves the screening decision

Reverse bias V	0–20 V	20–40 V	40–150 V	150 V to V _{bd}
Step size	4 V	2 V	10 V	2 V



Reference scan



Segmented scan: early validation example

Early validation example: $V_{bd} = 186\text{--}188\text{ V}$.

Conclusion: Matched comparisons support CQC screening and SQC cross-checks.

Fine steps near breakdown support the segmented-scan method.

VBD maps and sensor classification

Channel-level breakdown maps and sensor-level selection criteria

The information used to distinguish different classes is plotted on GoodSensor map

Class A:

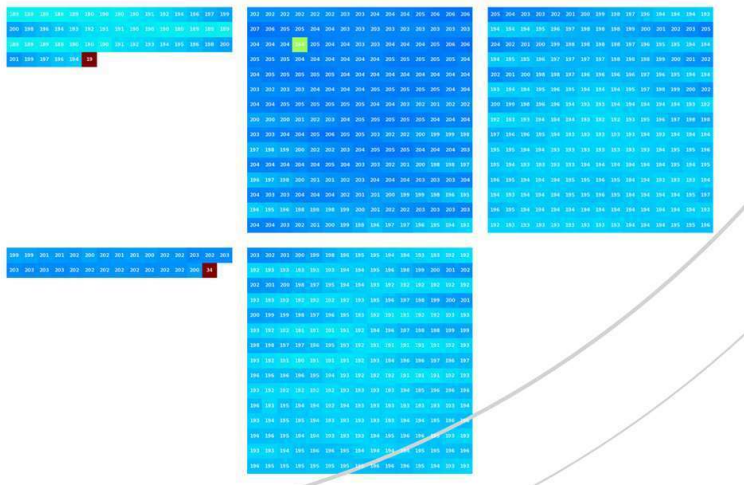
- $165V < 195V$
- $RMS/Mean \text{ for } V_{bd} < 0.05$
- $I_{ratio} \leq 2.5$

Class B1:

- $150V < 165V$
- $RMS/Mean \text{ for } V_{bd} < 0.05$
- $I_{ratio} \leq 2.5$

Class B2:

- $165V < 195V$
- $RMS/Mean \text{ for } V_{bd} < 0.05$
- $2.5 \leq I_{ratio} \leq 10$



Channel-level VBD map (detail)

46 vbdmin = 19.742 V abs(vbdrms/vbdmean) = 0.128 imax2imin = 3.298 51	47 vbdmin = 164.256 V abs(vbdrms/vbdmean) = 0.019 imax2imin = 1.707 B1	48 vbdmin = 192.634 V abs(vbdrms/vbdmean) = 0.014 imax2imin = 1.537 Pass
50 vbdmin = 34.464 V abs(vbdrms/vbdmean) = 0.156 imax2imin = 13.088 29	49 vbdmin = 190.929 V abs(vbdrms/vbdmean) = 0.013 imax2imin = 1.56 Pass	Avg Temp: 22.07 °C Pass Rate: 39/52 (75.0%) B1 Rate: 2/52 (3.8%) B2 Rate: 0/52 (0.0%) Good Sensor VBD Avg: 184.48 V

Sensor classes and wafer statistics (detail)

USTC-IME LGAD production

production started in 2026, with all batches have been obtained for now

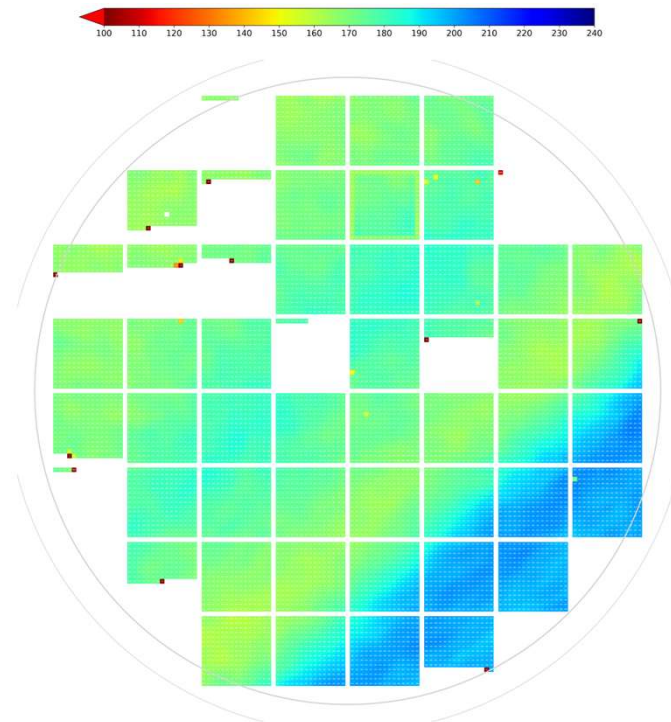
- Batch Pilot and Batch K1
Received at 1.31 2026
- Batch K2, K3 and K4
Received at 3.2 2026
- CQC testing has been fully completed and the expected target quantity has been achieved



Single-wafer samples: K4-W13

Pass: 21 / 52 (40.4%) B1: 11 / 52 B2: 0

Mean temperature: 24.65 °C Mean |VBD| of good sensors: 172.18 V



Channel-level |VBD| map (V)

	01	02	03	04	
	vbdmin = 116 V abs(vbdms/vbdmean) = 0.356 imax2min = 1.02	vbdmin = 163.7 V abs(vbdms/vbdmean) = 0.011 imax2min = 1.594	vbdmin = 164.664 V abs(vbdms/vbdmean) = 0.014 imax2min = 1.618	vbdmin = 167.375 V abs(vbdms/vbdmean) = 0.014 imax2min = 1.562	
	9	B1	B1	Pass	
10	vbdmin = 23.446 V abs(vbdms/vbdmean) = 0.064 imax2min = 3.018	09	vbdmin = 29.309 V abs(vbdms/vbdmean) = 0.147 imax2min = 1.034	08	vbdmin = 166.087 V abs(vbdms/vbdmean) = 0.009 imax2min = 1.622
	184	32	Pass	Fail	07
					vbdmin = 163.846 V abs(vbdms/vbdmean) = 0.027 imax2min = 5.907
					06
					vbdmin = 142.352 V abs(vbdms/vbdmean) = 0.023 imax2min = 1.796
					05
					vbdmin = 108.339 V abs(vbdms/vbdmean) = 0.0 imax2min = 1.0
					1
11	vbdmin = 15.402 V abs(vbdms/vbdmean) = 0.086 imax2min = 1.649	12	vbdmin = 4.904 V abs(vbdms/vbdmean) = 0.119 imax2min = 3.64	13	vbdmin = 76.527 V abs(vbdms/vbdmean) = 0.076 imax2min = 2.542
	91	72	54	Pass	14
					vbdmin = 172.772 V abs(vbdms/vbdmean) = 0.011 imax2min = 1.616
26	vbdmin = 165.826 V abs(vbdms/vbdmean) = 0.009 imax2min = 1.521	25	vbdmin = 143.2 V abs(vbdms/vbdmean) = 0.016 imax2min = 5.651	24	vbdmin = 171.306 V abs(vbdms/vbdmean) = 0.021 imax2min = 1.591
	Pass	Fail	Pass	8	23
					vbdmin = 116 V abs(vbdms/vbdmean) = 0.381 imax2min = 1.329
27	vbdmin = 9.22 V abs(vbdms/vbdmean) = 0.067 imax2min = 9.875	28	vbdmin = 166.757 V abs(vbdms/vbdmean) = 0.018 imax2min = 1.675	29	vbdmin = 178.005 V abs(vbdms/vbdmean) = 0.009 imax2min = 1.664
	207	Pass	Pass	Pass	30
					vbdmin = 171.889 V abs(vbdms/vbdmean) = 0.017 imax2min = 1.603
42	vbdmin = 102.804 V abs(vbdms/vbdmean) = 0.175 imax2min = 1.414	41	vbdmin = 173.512 V abs(vbdms/vbdmean) = 0.013 imax2min = 1.621	40	vbdmin = 172.373 V abs(vbdms/vbdmean) = 0.015 imax2min = 1.604
	5	Pass	Pass	Pass	39
					vbdmin = 165.536 V abs(vbdms/vbdmean) = 0.018 imax2min = 1.634
					38
					vbdmin = 164.245 V abs(vbdms/vbdmean) = 0.018 imax2min = 1.564
					37
					vbdmin = 169.382 V abs(vbdms/vbdmean) = 0.045 imax2min = 1.643
					36
					vbdmin = 184.1 V abs(vbdms/vbdmean) = 0.011 imax2min = 1.642
					35
					vbdmin = 171.117 V abs(vbdms/vbdmean) = 0.012 imax2min = 1.648
					Pass
					43
					vbdmin = 19.285 V abs(vbdms/vbdmean) = 0.08 imax2min = 2.531
					44
					vbdmin = 161.829 V abs(vbdms/vbdmean) = 0.018 imax2min = 1.575
					45
					vbdmin = 163.35 V abs(vbdms/vbdmean) = 0.018 imax2min = 1.64
					46
					vbdmin = 165.964 V abs(vbdms/vbdmean) = 0.048 imax2min = 1.76
					47
					vbdmin = 185.341 V abs(vbdms/vbdmean) = 0.014 imax2min = 1.661
					48
					vbdmin = 195.168 V abs(vbdms/vbdmean) = 0.01 imax2min = 1.483
					Fail
					52
					vbdmin = 159.913 V abs(vbdms/vbdmean) = 0.021 imax2min = 1.49
					51
					vbdmin = 165.114 V abs(vbdms/vbdmean) = 0.021 imax2min = 1.574
					50
					vbdmin = 184.48 V abs(vbdms/vbdmean) = 0.019 imax2min = 1.572
					49
					vbdmin = 64.884 V abs(vbdms/vbdmean) = 0.053 imax2min = 1.505
					167

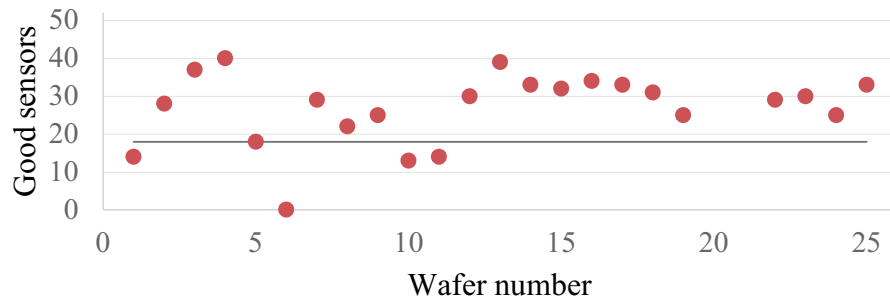
Avg Temp: 24.65 °C
 Pass Rate: 21/52 (40.4%)
 B1 Rate: 11/52 (21.2%)
 B2 Rate: 0/52 (0.0%)
 Good Sensor VBD Avg: 172.18 V

Sensor classification map

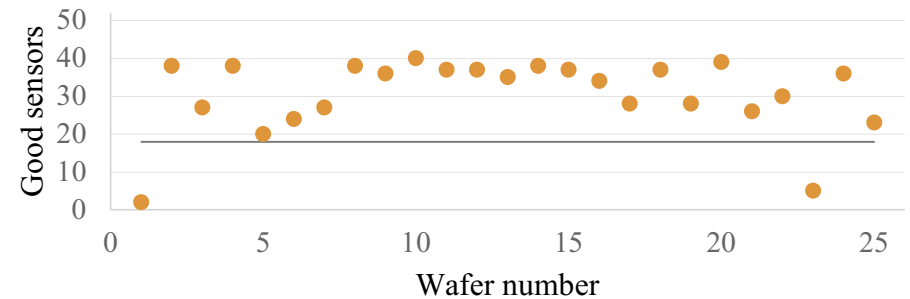
Yield across all K1–K4 wafers

Selection threshold: 18 good sensors per wafer

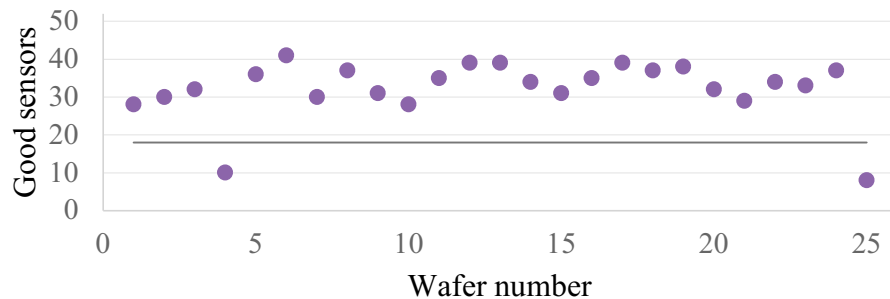
All recorded production wafers shown. Each wafer contains 52 main sensors



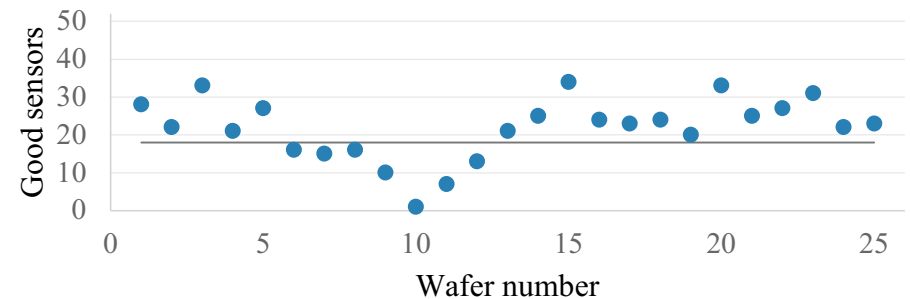
K1: 19 / 23 wafers selected



K2: 23 / 25 wafers selected



K3: 23 / 25 wafers selected

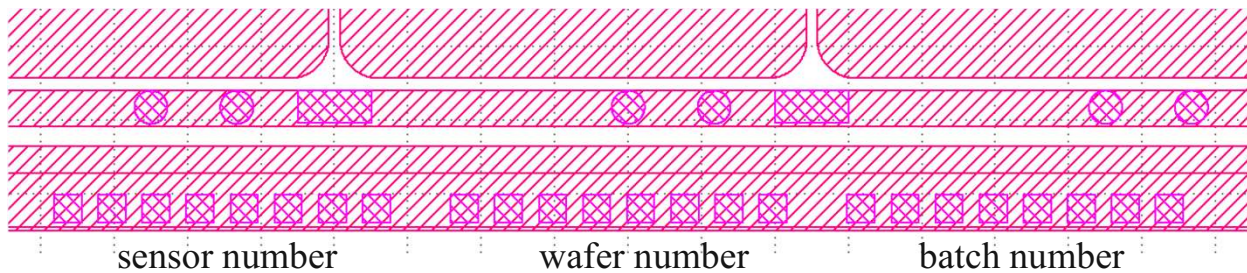


K4: 18 / 25 wafers selected

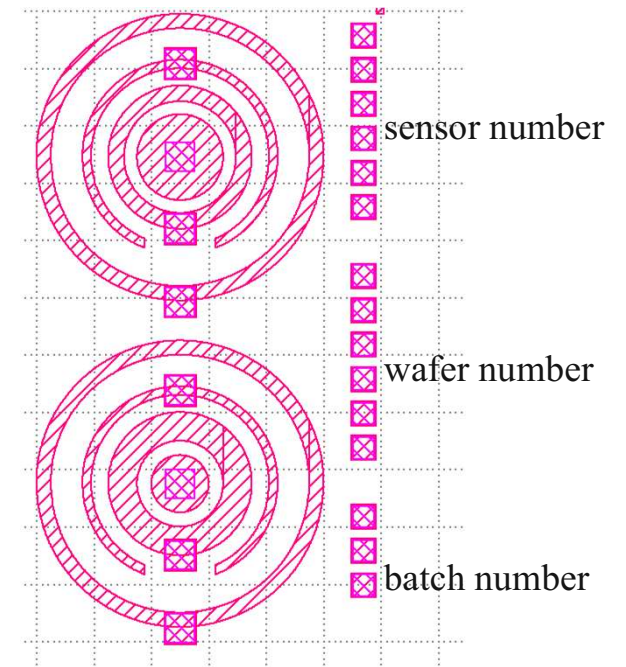
Scratch marking: encoded sensor identification

All planned scratch marking complete

Binary code: sensor number, wafer number and batch number



Encoding layout at the first marker location



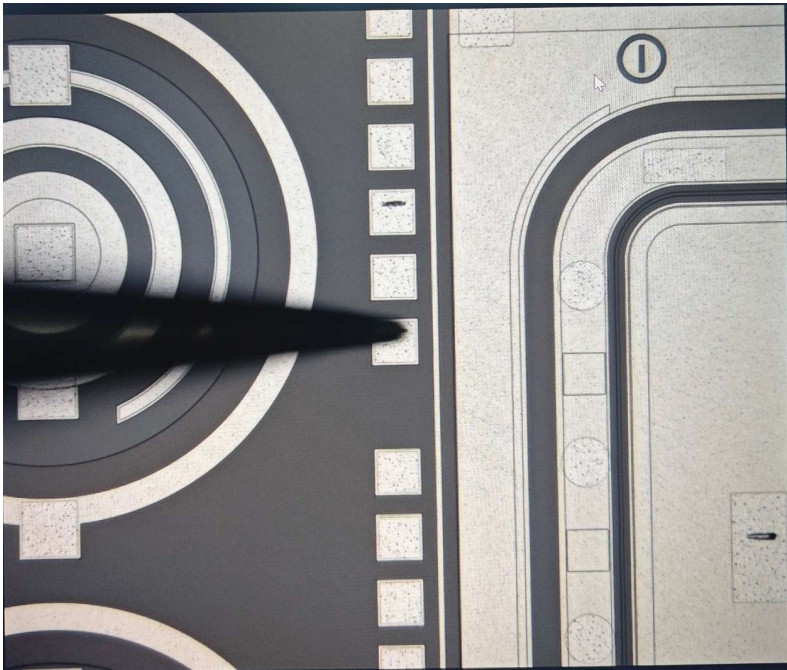
Second marker location

Identification for sensor traceability

Scratch-marker implementation

Two marker locations use separate alignment maps

Software adjustments and alignment checks supported the marking campaign



Scratch marks at the encoded positions

	qcts-marker_Batch04_Wafer03.map	185=13,-2,25,-1,Skipped,0,0,0
	qcts-marker_Batch04_Wafer04.map	186=13,-2,24,-1,ToBeProbed,0,0,0
	qcts-marker_Batch04_Wafer05.map	187=13,-2,23,-1,Skipped,0,0,0
	qcts-marker_Batch04_Wafer06.map	188=13,-2,22,-1,Skipped,0,0,0
	qcts-marker_Batch04_Wafer07.map	189=13,-2,21,-1,ToBeProbed,0,0,0
	qcts-marker_Batch04_Wafer08.map	190=13,-2,20,-1,Skipped,0,0,0
	qcts-marker_Batch04_Wafer09.map	191=13,-2,19,-1,Skipped,0,0,0
	qcts-marker_Batch04_Wafer10.map	192=13,-2,18,-1,ToBeProbed,0,0,0
	qcts-marker_Batch04_Wafer11.map	193=13,-2,17,-1,ToBeProbed,0,0,0
	qcts-marker_Batch04_Wafer12.map	194=13,-2,16,-1,Skipped,0,0,0
	qcts-marker_Batch04_Wafer13.map	195=13,-2,15,-1,Skipped,0,0,0
	qcts-marker_Batch04_Wafer14.map	196=14,-1,29,-1,Skipped,0,0,0
	qcts-marker_Batch04_Wafer15.map	197=14,-1,28,-1,Skipped,0,0,0
	qcts-marker_Batch04_Wafer16.map	198=14,-1,27,-1,ToBeProbed,0,0,0
		199=14,-1,26,-1,ToBeProbed,0,0,0
		200=14,-1,25,-1,ToBeProbed,0,0,0
		201=14,-1,24,-1,Skipped,0,0,0
		202=14,-1,23,-1,Skipped,0,0,0
		203=14,-1,22,-1,Skipped,0,0,0
		204=14,-1,21,-1,ToBeProbed,0,0,0
		205=14,-1,20,-1,Skipped,0,0,0
		206=14,-1,19,-1,Skipped,0,0,0

Wafer-specific marker maps

Status of USTC-IME production testing

Pilot and K1–K4 CQC testing complete

Work item	Status	Results
CQC testing	Complete	85 selected wafers, 2,632 good sensors
Database upload	Complete	Sensor-level CQC and I–V records
Scratch marking	Complete	Encoded sensor, wafer and batch IDs

121 tested wafers

59.5% yield on selected wafers

Wafer selection: at least 18 good sensors out of 52

Summary

USTC–IME sensors: performance validation and production quality control

Performance established with irradiated prototypes

Charge > 4 fC, sensor timing < 50 ps, efficiency $> 95\%$ at suitable bias

QC procedures supported by independent cross-checks

Matrix I–V / C–V, controlled-temperature tests and QC-TS radiation monitoring

Production CQC complete

121 wafers tested; 85 selected wafers; 2,632 good sensors; 59.5% sensor yield

Database upload and scratch marking complete

UBM, AOI and dicing in progress

Thanks!

Back up

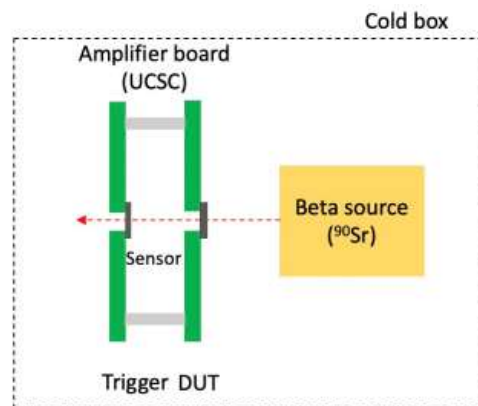
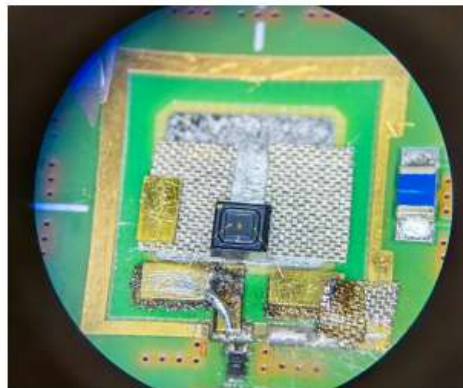
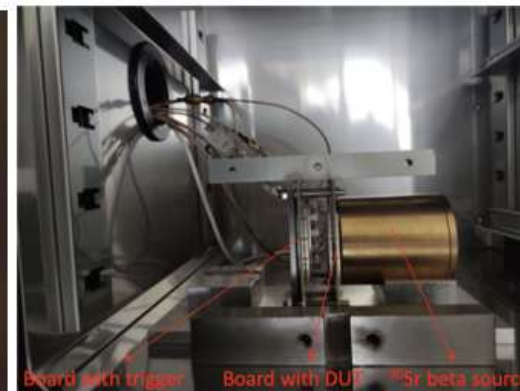
Backup: β -source performance measurements

Laboratory charge and timing measurements support prototype qualification

^{90}Sr source and a reference LGAD in coincidence

UCSC amplifier boards, oscilloscope: 1 GHz / 20 GS/s

Temperature-controlled chamber for irradiated sensors



USTC β -scope: coincidence layout, bonded sensor and laboratory setup

Backup: beam-test setup and conditions

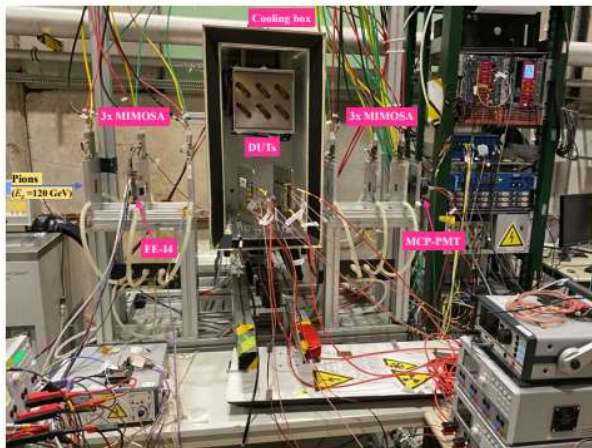
Tracking measures hit position, while the MCP-PMT provides a time reference

CERN: 120 GeV pions, USTC devices at $-30\text{ }^{\circ}\text{C}$

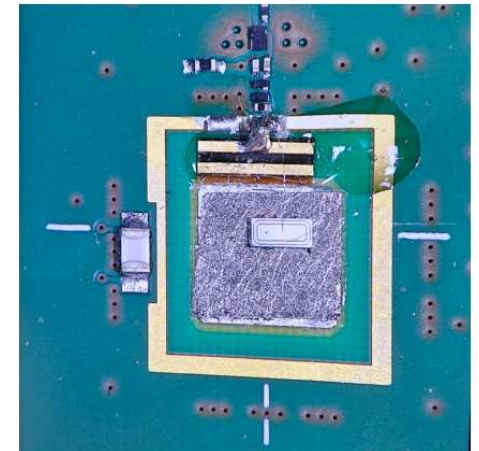
Six MIMOSA tracking planes, MCP-PMT time reference

Waveform digitization: 1 GHz / 6.25 GS/s

Setup variation: 10% systematic uncertainty in charge and timing



CERN and DESY beam-test installations



Single-pad QC-TS
on the readout board

Backup: collected-charge reconstruction

Pulse integration gives charge, the fitted MPV defines the performance metric

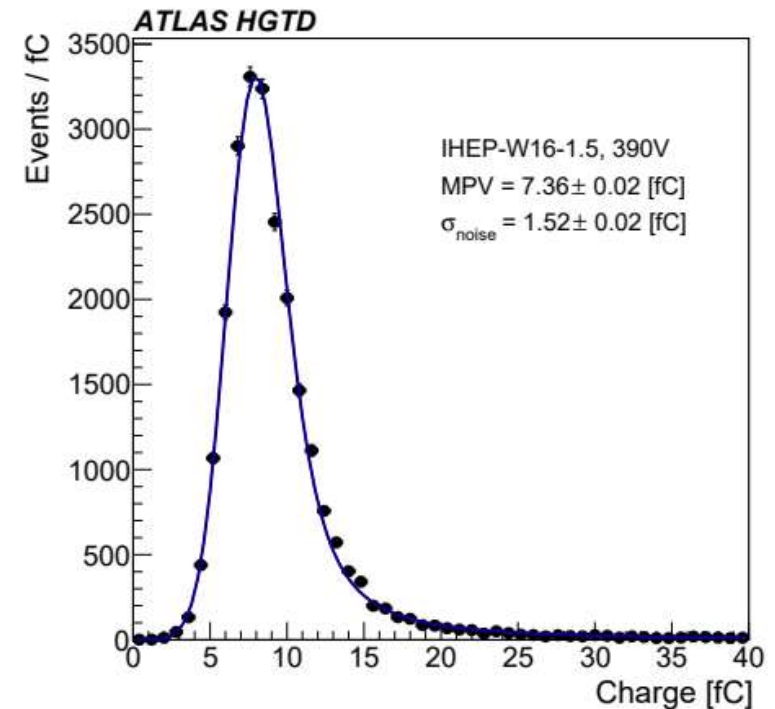
1. Subtract the event-by-event baseline
2. Integrate the signal over the pulse
3. Convert with calibrated readout gain
4. Fit the charge distribution

$$Q = \int [V(t) - V_{\text{baseline}}] dt / Z_{\text{eff}}$$

Z_{eff} includes the full readout chain.

Landau–Gaussian fit

MPV = 7.36 ± 0.02 fC (stat.)



Published method example: IHEP-W16-1.5
390 V, -30 °C

Backup: CFD and time-resolution extraction

The reference contribution is removed from the time-difference width

50% constant-fraction crossing

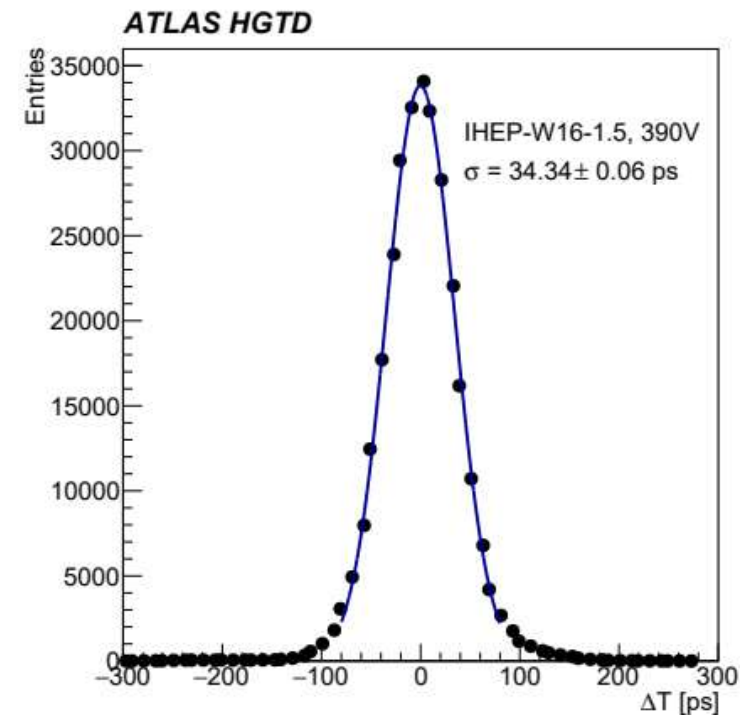
Linear interpolation between samples

$\Delta t = t_{\text{DUT}} - t_{\text{MCP}}$, Gaussian fit

$$\sigma_{\text{DUT}} = \sqrt{(\sigma_{\Delta t}^2 - \sigma_{\text{MCP}}^2)}$$

$$\sigma_{\text{MCP}} = 10.6 \pm 2.2 \text{ ps}$$

Example: 34.34 ps width
corresponds to $\sigma_{\text{DUT}} \approx 32.7 \text{ ps}$



Published method example: IHEP-W16-1.5
390 V, -30°C

Backup: efficiency and operating-point definition

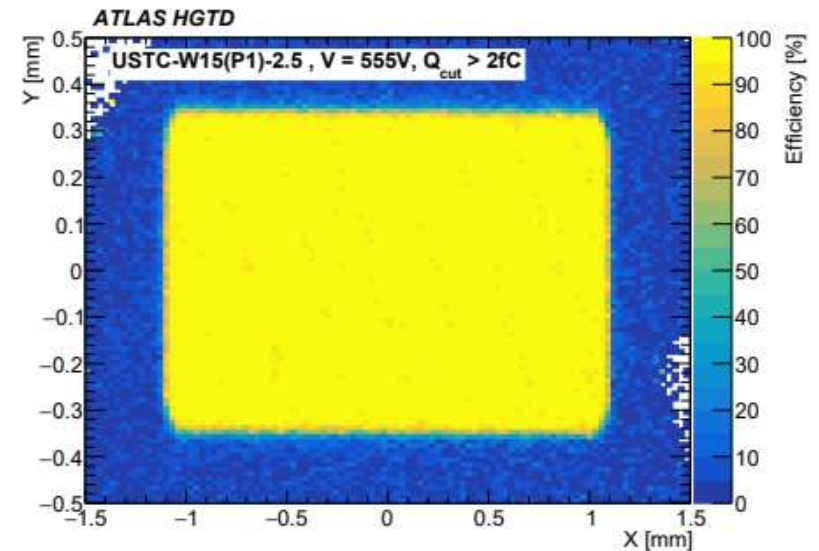
Efficiency requires an independent track denominator and a stated threshold

$$\varepsilon = N(\text{tracks with } Q > 2 \text{ fC}) / N(\text{selected tracks})$$

Central-pad ROI
excludes the physical edge

2 fC hit threshold
4 fC charge-MPV requirement

Operating point: charge, timing,
efficiency and breakdown margin



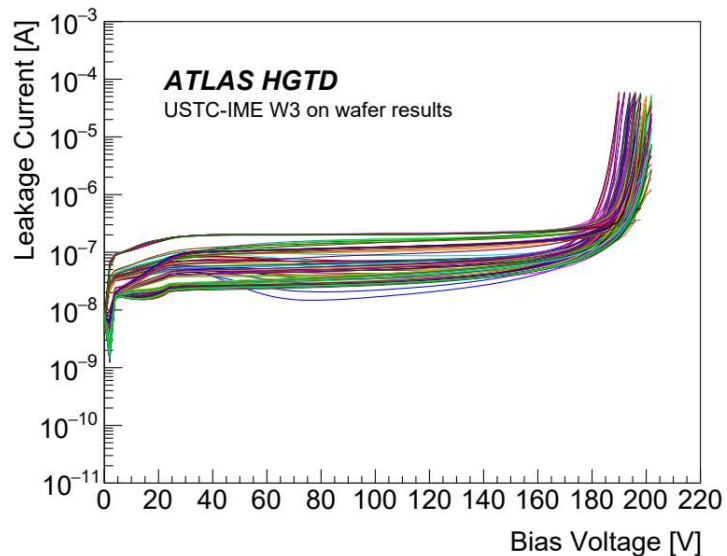
USTC-W15(P1), 2.5×10^{15} neq/cm²
-30 °C, published map at 555 V

Backup: complete CQC–SQC I–V comparison

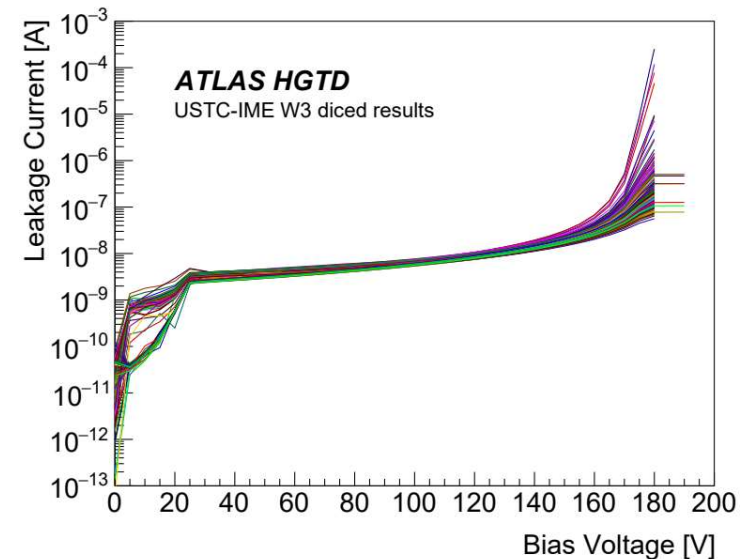
Common bias improves the relevance of the array-uniformity measurement

Same W3 pre-production sensor, different measurement configurations

Comparison of V_{bd} requires matched temperature and contact conditions



Wafer: probe needles, other pads floating



Diced sensor: matrix probe card, 20 °C

Backup: why are other pads floating in CQC?

Sequential per-pad screening, followed by matrix SQC checks

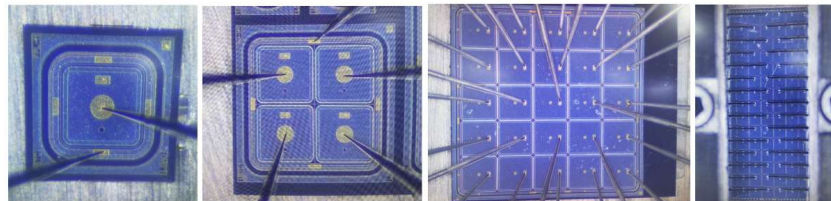
Electrode	CQC connection
Backside	Negative high voltage
Measured pad	Picoammeter, near 0 V
Other pads	Floating
Guard ring	Floating in this dataset

Practical wafer-level screening

Grounding all 225 pads requires a matrix probe card and switching system.

Why matrix SQC is needed

Floating contacts can affect edge leakage. SQC checks uniformity with other pads held at a common potential.



Probe contacts: single pad, 2×2 , 5×5 and 15×15 arrays

The source does not specify why GR was left floating.

Carbon doping preserves the gain layer

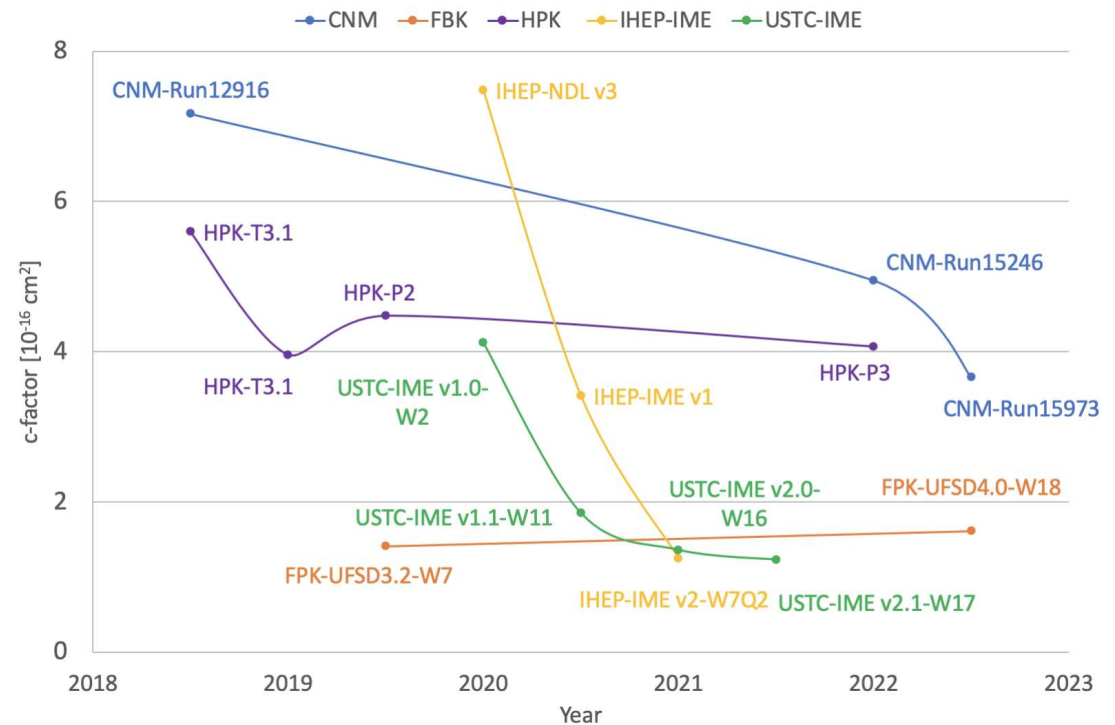
Radiation tolerance sets the operating-voltage margin

Radiation removes active acceptors and reduces multiplication.

$$V_{gl}(\Phi) / V_{gl}(0) = \exp(-c\Phi)$$

USTC v2.1 W17
 $c = 1.23 \times 10^{-16} \text{ cm}^2$

Smaller c:
more gain retained after irradiation
lower bias needed for the same charge



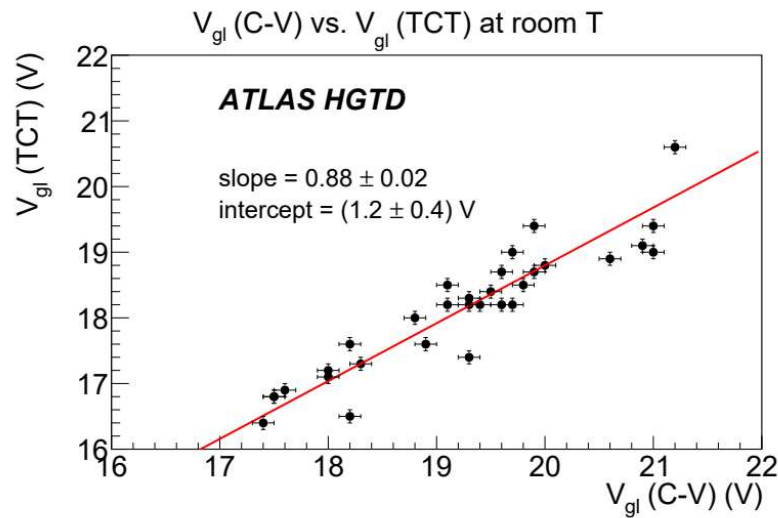
Acceptor-removal coefficient across prototype generations

Radiation monitoring linked to collected charge

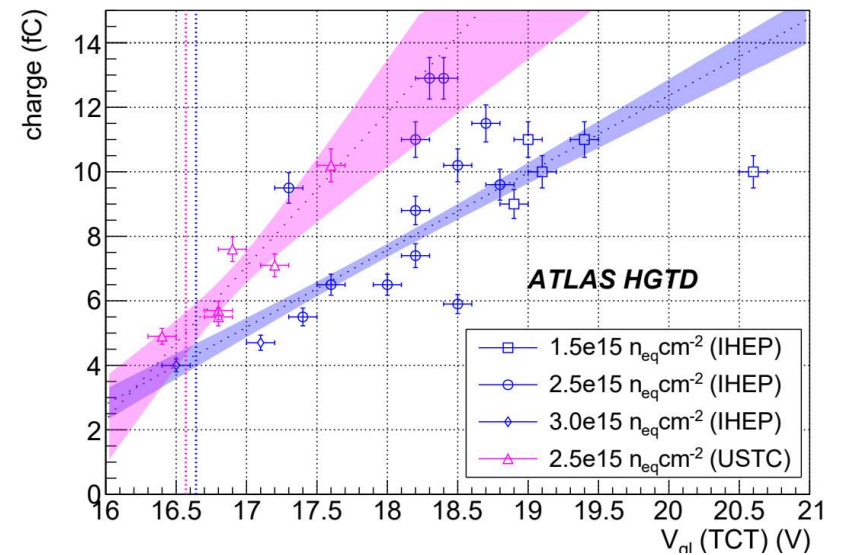
TCT observables are calibrated against C-V and β -source measurements

QC-TS: V_{gl} , gain at fixed bias, leakage and inactive inter-pad width

Correlations support wafer-level radiation screening with method-specific calibration.



V_{gl} from TCT versus C-V: correlated, with an offset

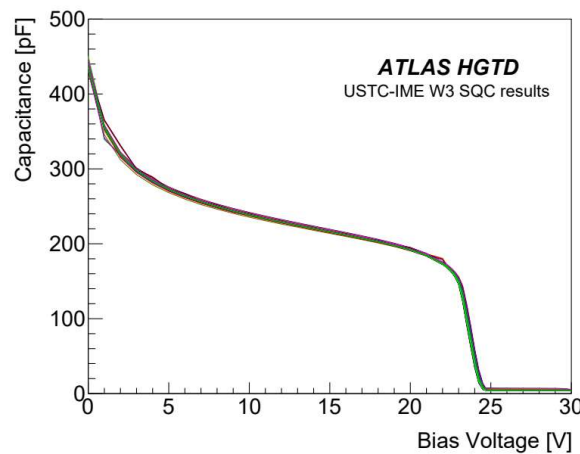
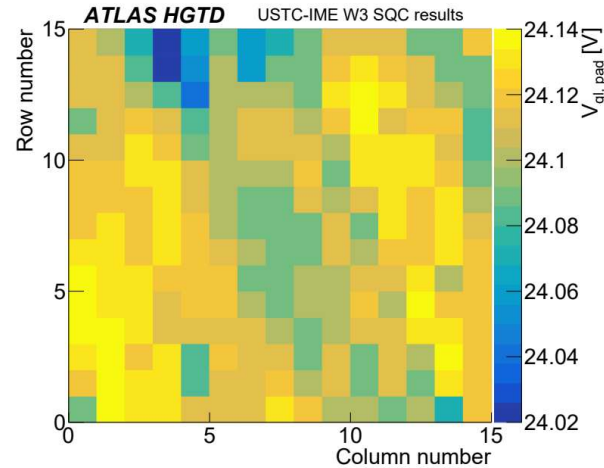


V_{gl} from TCT versus β -source collected charge

Uniformity across the full sensor

225 pads share a common bias, requiring a uniform gain layer

Quantity	HGTD criterion	Pre-production evidence
V _{gl} spread (RMS / mean)	< 0.5%	≈ 0.08% (W3)
Leakage spread, I _{max} / I _{min}	< 3	Pass with matrix measurement



225 C–V curves and V_{gl} map, USTC W3, 20 °C

Backup: why are other pads floating in CQC?

Sequential per-pad screening, followed by matrix SQC checks

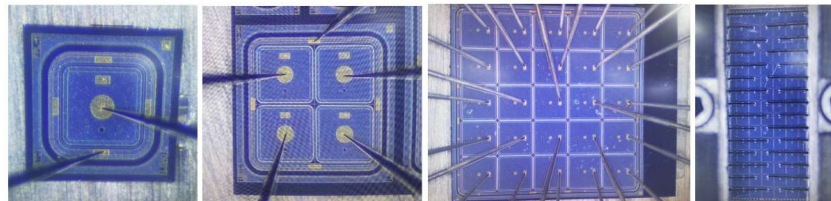
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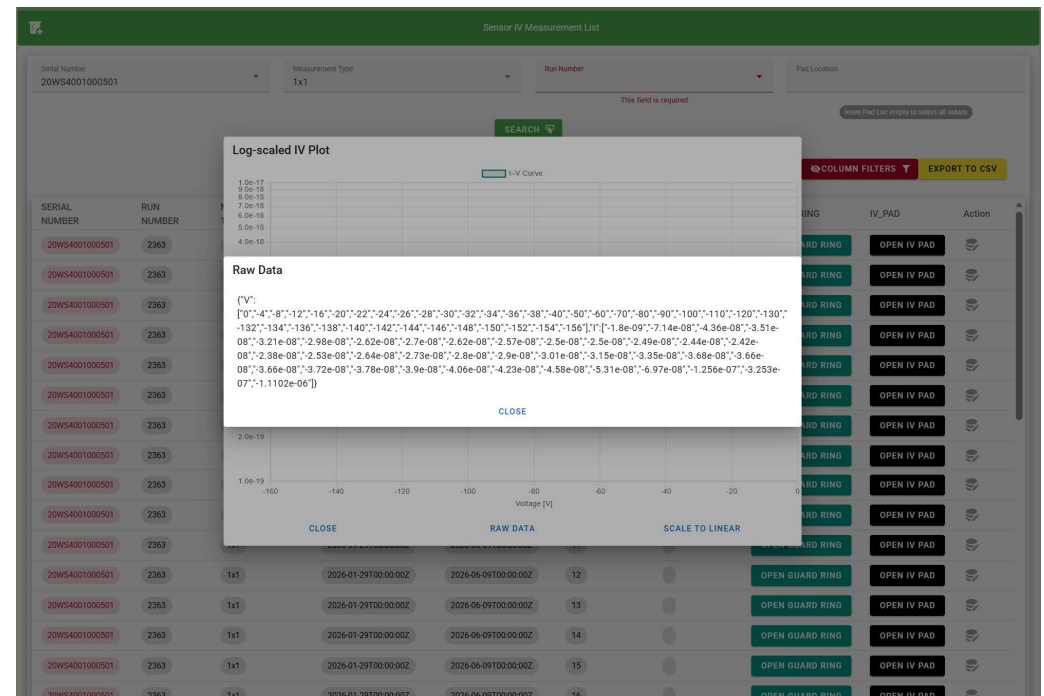
CQC data in the HGTD database

CQC records uploaded to the HGTD database

Manufacturer overview and individual sensor I–V records

Manufacturer Summary		
SR#	NAME	TOTAL
1	IHEP-IME	10729
2	test_manufacturer	9125
3	ProdDB-Virtual Manufacturer	8389
4	USTC-IME	6028
5	FT_Company_Germany	4227

USTC-IME manufacturer entry

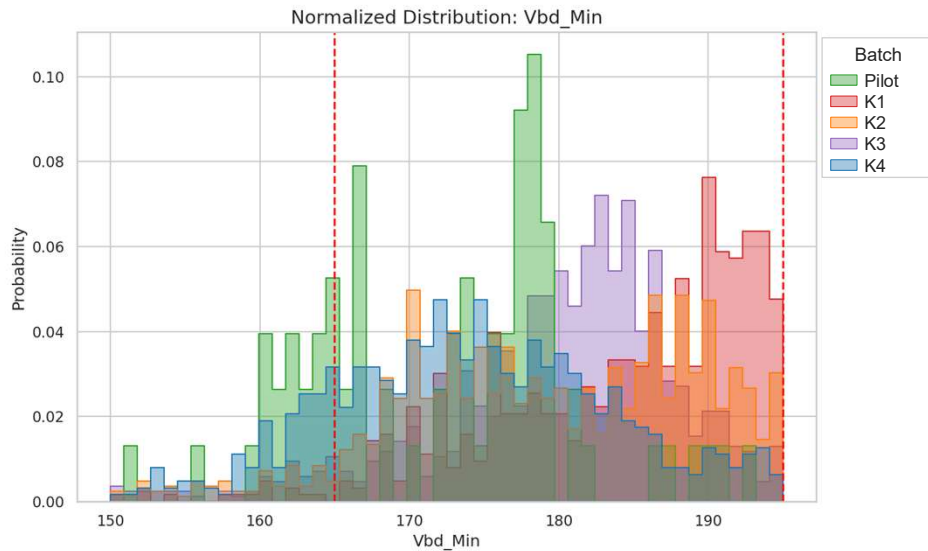


Example sensor: 20WS4001000501

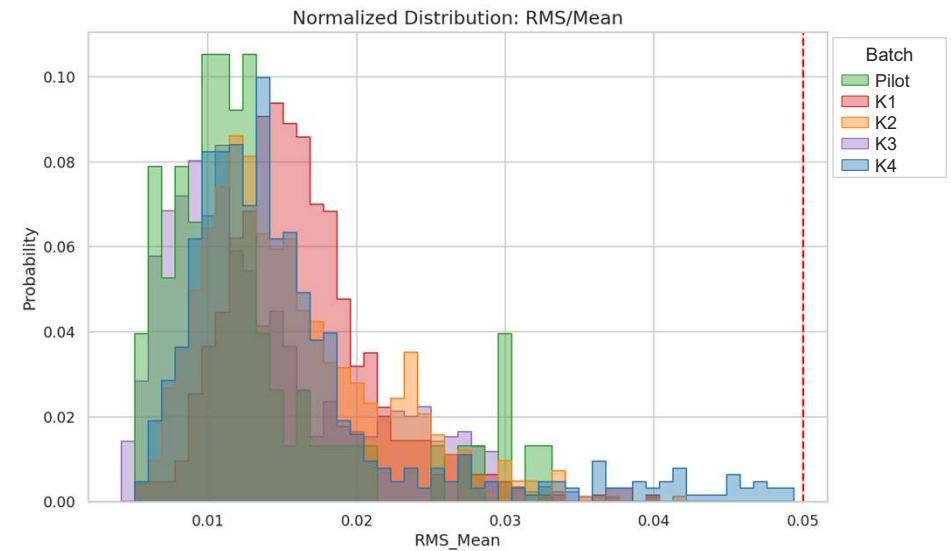
Breakdown voltage and channel uniformity

$V_{BD_{min}}$ and RMS distribution

- K4 shifts toward lower $|V_{BD}|_{min}$ relative to K1
- RMS / mean remains below 5% in the displayed sample



Minimum $|V_{BD}|$ distribution (V)

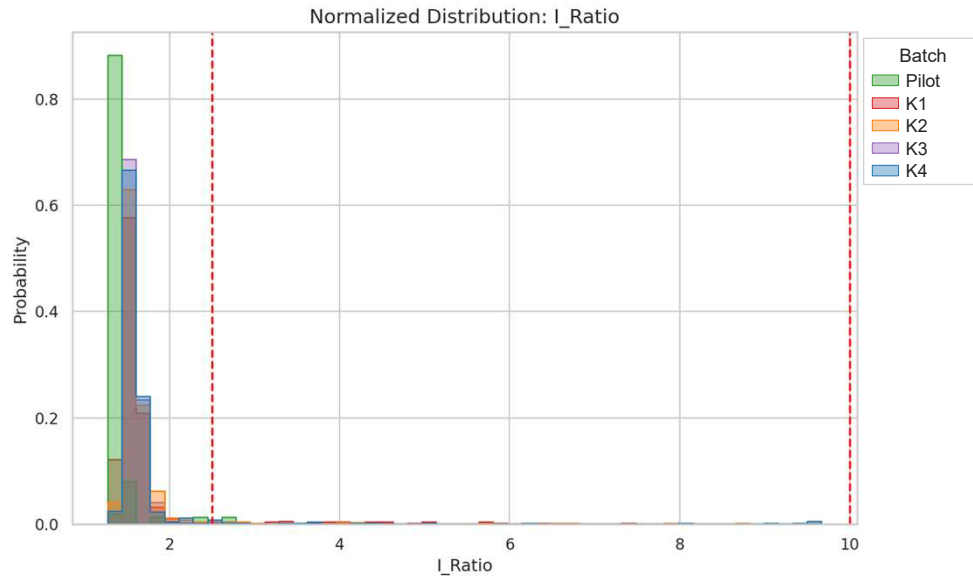


Relative spread: RMS / mean

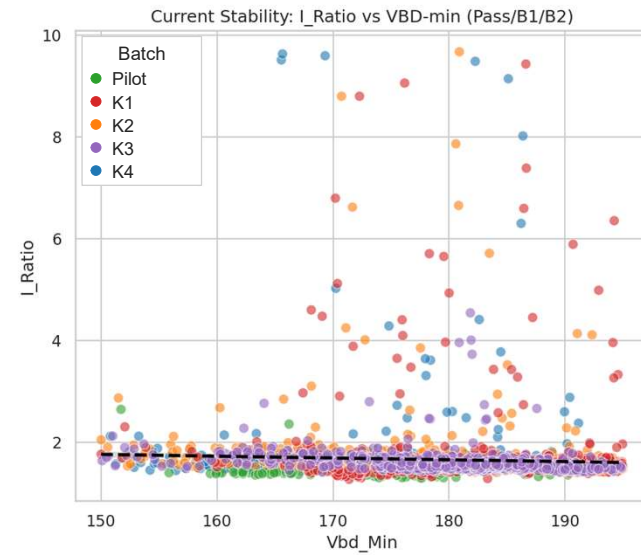
Leakage-current ratio

Most Iratio values cluster around 1.5–2

A small high-ratio tail requires channel-level I–V checks



Normalized Iratio distribution



Iratio versus $|V_{BD}|_{min}$ (V)

The data associates extreme ratios with premature breakdown

Backup: wafer counts for K1 and K2

Good sensors per wafer (52 main sensors per wafer)

Selected wafers: good-sensor count ≥ 18

Wafer	K1	K2	Wafer	K1	K2
W1	14	2	W14	33	38
W2	28	38	W15	32	37
W3	37	27	W16	34	34
W4	40	38	W17	33	28
W5	18	20	W18	31	37
W6	0	24	W19	25	28
W7	29	27	W20	—	39
W8	22	38	W21	—	26
W9	25	36	W22	29	30
W10	13	40	W23	30	5
W11	14	37	W24	25	36
W12	30	37	W25	33	23
W13	39	35			

Backup

An automatic probe station acquires channel-level reverse I–V curves at room temperature. Wafer identification, notch orientation, map alignment and probe contact are checked before scanning. Coverage and anomalous regions are reviewed before sensor classification. [2]

Reverse-bias magnitude V (V)	0–20	20–40	40–150	>150
Voltage step ΔV (V)	4	2	10	2

Table 2. Segmented scan settings. The listed voltages are magnitudes of the applied reverse bias.

For each wafer, the same designated pad position is measured with both the segmented scan and a fixed 2 V step to obtain a reference I–V curve. The consistency criterion is that the two extracted breakdown voltages fall within the same voltage-step interval of the segmented scan. The same pad is used for the paired measurements to avoid confounding the comparison with pad-to-pad variation.

Observable	Definition	Interpretation	
Minimum breakdown voltage	Minimum valid VBD over 225 channels	Detects premature local breakdown	165-195
Breakdown spread	$\text{RMS}(\text{VBD}) / \text{mean}(\text{VBD})$	Assesses channel uniformity	0.05
Leakage-current ratio	$I_{\text{max}} / I_{\text{min}}$ at a specified bias	Assesses leakage uniformity	3
Sensor class	Pass, B1, B2 or other source category	Combined electrical classification	

Background references

[1] Carbon-enriched gain layer

C. H. Li et al.
NIM A 1039 (2022) 167008
DOI: 10.1016/j.nima.2022.167008

[2] Early prototypes and radiation damage

Xiao Yang et al.
JUSTC 52(1) (2022) 3
DOI: 10.52396/JUSTC-2021-0204

[3] Pre-production beam tests

A. Aboulhorma et al.
JINST 21 (2026) P03021
arXiv: 2512.01855

[4] TCT monitoring for production

I. Velkovska et al.
NIM A 1084 (2026) 171195
arXiv: 2509.09187v2

[5] USTC first-batch AC-LGAD

Han Li et al.
arXiv: 2512.13152v1 (2025)
Design and fabrication: Section 2

[6] USTC development roadmap

Xiangxuan Zheng, PhD defence
HGTD background: pp.31–35
Versions: p.36, validation: p.48

Performance and QC references

Primary sources for the added characterization and method-validation slides

[1] Kuo Ma, USTC PhD thesis (2026)

Ch.5: requirements pp.64–66; performance pp.85–106; QC pp.107–116

Appendix C: process and temperature validation pp.195–196

[2] A. Aboulhorma et al., JINST 21 (2026) P03021

Pre-production beam tests: charge, sensor timing and efficiency

arXiv:2512.01855

[3] I. Velkovska et al., NIM A 1084 (2026) 171195

TCT-based monitoring of radiation hardness

arXiv:2509.09187v2

[4] K. Ma, CLHCP 2024; X. Zheng, 43rd RD50 (2023)

USTC–IME pre-production characterization and independent probe-station tests